Popper & the EPR Experiment

LSE 4.12.02

1. EPR experiment purports to show simultaneous sharp values for x and p for an electron i.e. the incompleteness of QM.
   So electrons do have sharp trajectories

2. cp Single slit expt.
   Popper & Einstein believe in sharp trajectories but differ concerning determinism.
   Heisenberg believes lack of simultaneous knowledge of x & p means it is meaningless to talk about them (positivism)
   Bohr thinks they don't have sharp values hence we can't have simultaneous knowledge

3. Popper 1934 Expt
4. EPR (1935)
5. Popper 1982 Expt.
6. Redhead's response to Popper
7. 1999 Kim–Shih Experiment.

Popper and the EPR Experiment

LSE 4.12.02

① Popper's criticism of Copenhagen that knowledge can produce physical effects

Show slide ⑪ on single slit experiment

Popper believes uncertainty principle is about objective scatter relations, not subjective states of knowledge.

② The EPR experiment seemed to show that x & p could both be sharp although not both known values
realist interpretation of QM
(but cf Bell → nonlocality for realist interpretation)

predictability v. predictedness.

③ Popper 1982 experiment expected to show Copenhagen committed to nonlocality or violation of uncertainty principle.

④ But Copenhagen is an interpretation of the formalism – cannot contradict the formalism. Uncertainty principle is a theorem of the formalism so can Popper's experiment show that QM is false? – a much stronger claim.

Popper and the Quantum Theory

Introduction

Popper wrote extensively on the quantum theory. In Logik der Forschung he devoted a whole chapter to quantum theory while the whole of vol 3 of the Postscript is devoted to this topic *

In this paper I will look at some of Popper's arguments, in a suitably critical spirit;

But he would have applauded this.

My great regret is that he cannot respond to this paper, with further criticisms of my arguments.

* He also gave an insightful critique of the 1936 paper of Birkhoff and von N. on non-distributive quantum logics

Render here is to prove
unique complementation which
together with orthocomplementation ⇒
Boolean lattice.

But his proof of unique complementation in quantum theory is flawed

Popper also tries to interpret complement of negation as a proposition in terms of the set-theoretic complement in Hilbert space rather than the ortho complement.

B & N in their paper do rather confusingly talk about complement when they should say orthocomplement 'linguistic confusion'

cf critique of Popper's 1968 paper by E Scheibe BJPS 1974

Pippard and the Quantum Theory

Quotations & Refs.

Popper and the Quantum Theory

1- Thought Experiments

In Logik der Forschung Popper devotes a whole chapter to quantum theory. This ch IX (in the 1959 translation) is entitled "Some observations on the Quantum Theory". In 1934 ~~the same year~~ (1934) Popper ~~had~~ published a short note in Die Naturwissenschaften entitled "Zur Kritik der Ungenauigkeitsrelationen". This was actually Popper's scientific debut. It contained what Popper later described as "a gross mistake for which I have been deeply sorry and ashamed ever since" (Postscript III, p. 15). Appendix *XII reproduces a letter from Einstein written in 1935 criticizing Popper's proposed thought experiment. Although he tells us in Unended Quest (p. 92) that he had defended his experiment against von Weisssäcker and Heisenberg, he immediately conceded Einstein's criticism. Nevertheless, in a sense, Popper had anticipated part of the thinking in the EPR paper of 1935. One can even speculate that Einstein was influenced by Popper here. (See Jammer p 178) Popper remarks in a letter to Jammer in 1967, with characteristic humility: "the possibility that a gross mistake made by a nobody (like myself) may have had an influence on a man like Einstein never entered my head".

Briefly, Popper's idea was to consider the scattering of two particles, call them A and B, of known momentum for A and of position for B. On particle A he measures the momentum and then the position and retrodicts back to the ~~position~~ time of the scattering event.

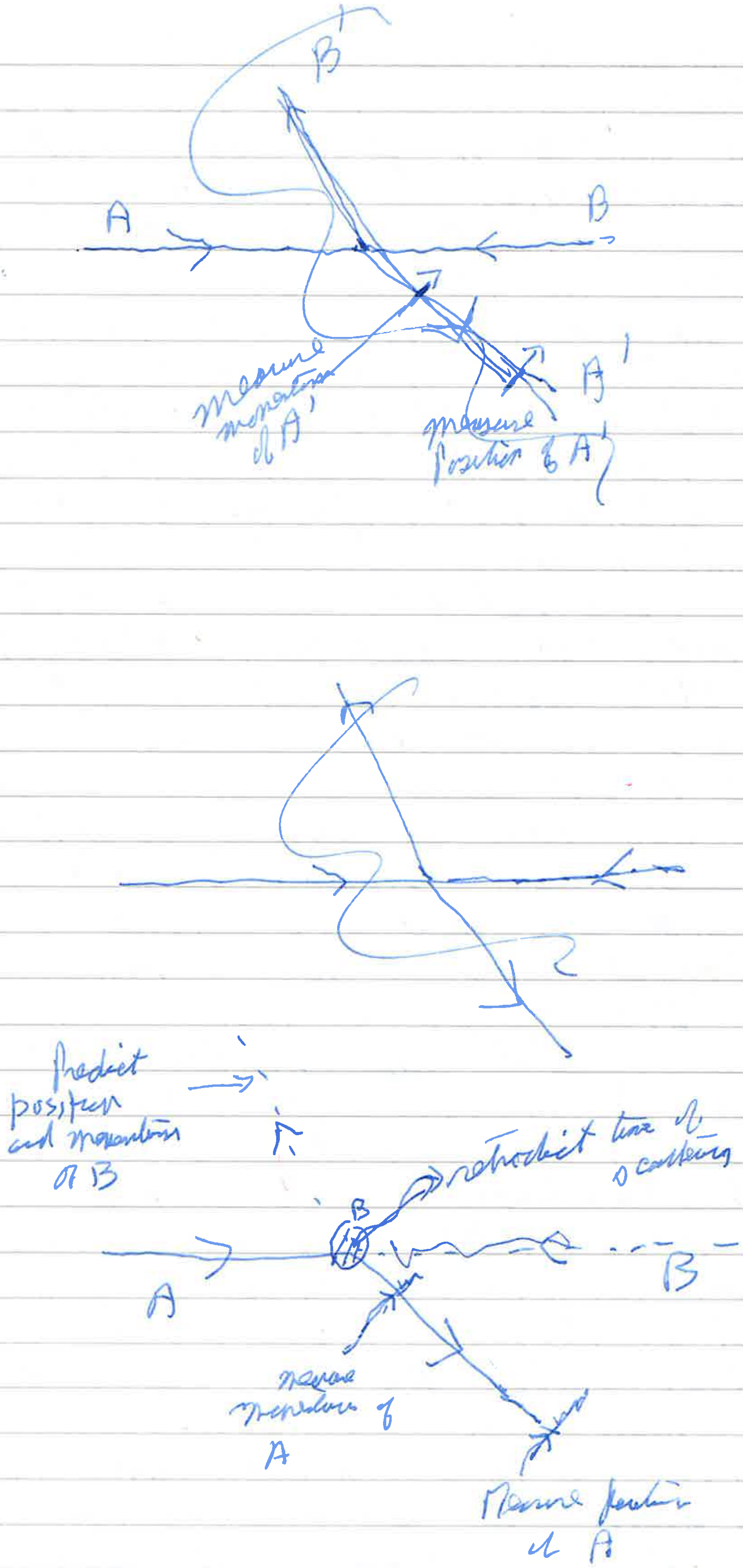
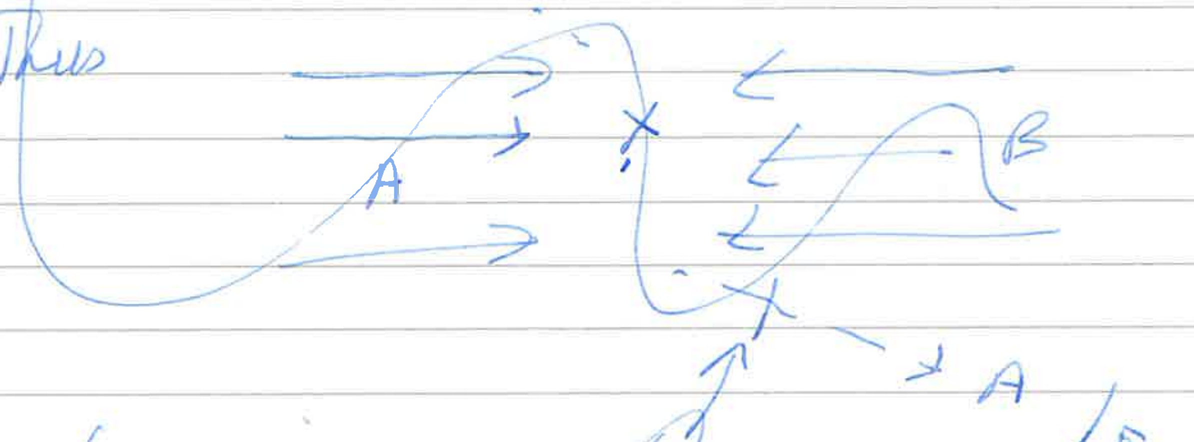

B'
A
B
Measure momentum of A'
Measure position of A'
A'
Predict position and momentum of B
B
retrodict time of scattering
A
B
measure momentum of A
Measure position of A

Fig 1.

But knowing the final momentum of A, conservation of measured momentum gives the magnitude of the momentum of ~~time~~ B (and also its initial vector momentum) and from its momentum at the time ~~location~~ of the scattering event, Popper could predict both the position and momentum of B. for any later time [This is illustrated in Fig. 9.]

Thus



measure momentum of A, or its position

so we construct its trajectory to point of collision at x

So by measurement on the A particle Popper could predict both momentum and position of ~~A~~ B

The 'mistake' is that measurement of momentum does ~~alter~~ the position of the A particle, so ~~we~~ deflects cannot retrodict to the time of collision ~~find the point~~ x, and hence cannot predict the position ~~trajectory~~ of B.

What EPR do is to describe an experiment in which by measuring either p or x on A we can predict either p or x on B – the affinity with Popper is clear but EPR need a counterfactual formulation to claim that x and p on B are simultaneous elements of reality.

Popper returned to the question of thought experiments in Appendix *XII (L Sc. D), entitled "On the use and misuse of Imaginary Experiments, Especially in Quantum Theory". Popper warns against the apologetic use of imaginary experiments. Great care must be taken not to introduce idealizations or other special assumptions unless they are favourable to an opponent, or such that any opponent would have to accept them.

Then in 1982, in the introduction to 'Quantum Theory and the Schism in Physics' (p27 ff.) Popper introduced a new thought experiment which he described as "an extension of the 'EPR argument'", to test the 'Copenhagen interpretation' of the uncertainty relations i.e. whether "knowledge alone is sufficient to create 'uncertainty', and with it, scatter".

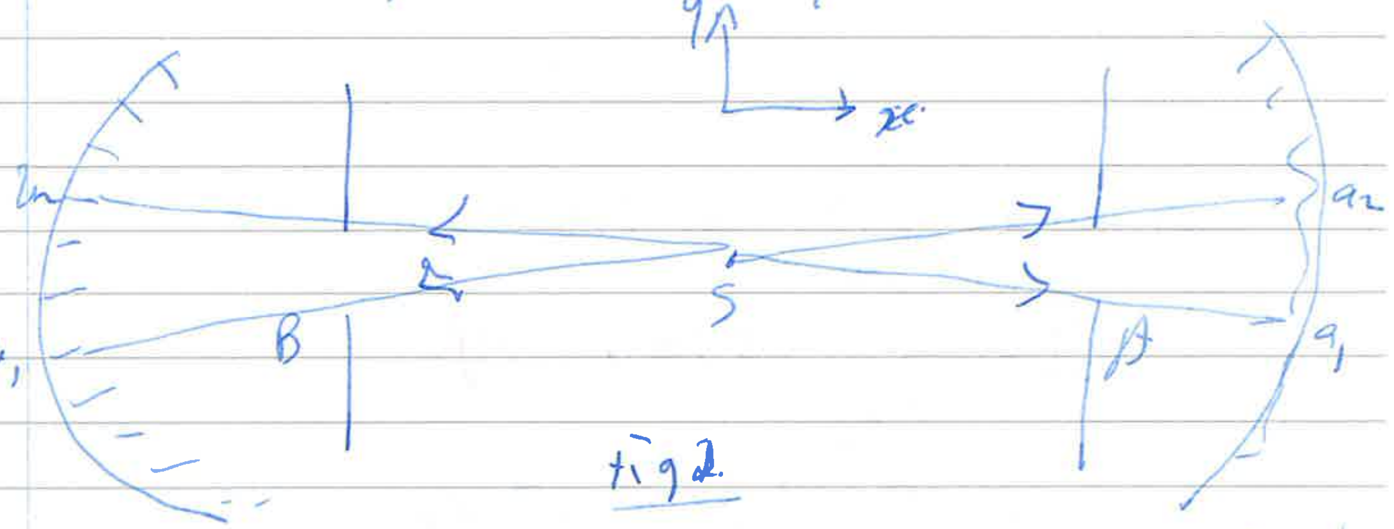


fig 2.

Popper suggests a source at S of positronium (see fig 2) from which pairs of particles are emitted in opposite directions. They are selected through slits A and B, initially with a wide gap, so there is no appreciable diffraction, and fire off, in coincidence, counters between b_1 and b_2 on the left, and a_1 and a_2 on the cf EPR state for transverse dimension

$$\Psi_0 = \int_{-\infty}^{\infty} |y\rangle \otimes |y\rangle \, dy.$$

$$= \int_{-\infty}^{\infty} |p_y\rangle \otimes |-p_y\rangle \, dp_y$$

So $$\langle \Psi_t | A_1 | \Psi_t \rangle = \int_{-\infty}^{\infty} \langle y_t | A_1 | y_t \rangle \, dy.$$

where A_1 is an observable referring to particle 1

$|y_t\rangle$ is time-evolved state at t which starts at $t=0$

as an eigenstate of position

right. Since the momenta are correlated, p_1 goes with q_2 and p_2 with q_1, and so on. But says Popper, their positions are also correlated, so if we narrow down slit A, then we are measuring its y coordinate and hence as a result of the position correlation, also the y-coordinate of the particle passing thru ~~through~~ B, so their transverse momentum scatters as they would give wide angle scatters from p_1' to p_2'. (See Fig. 3)

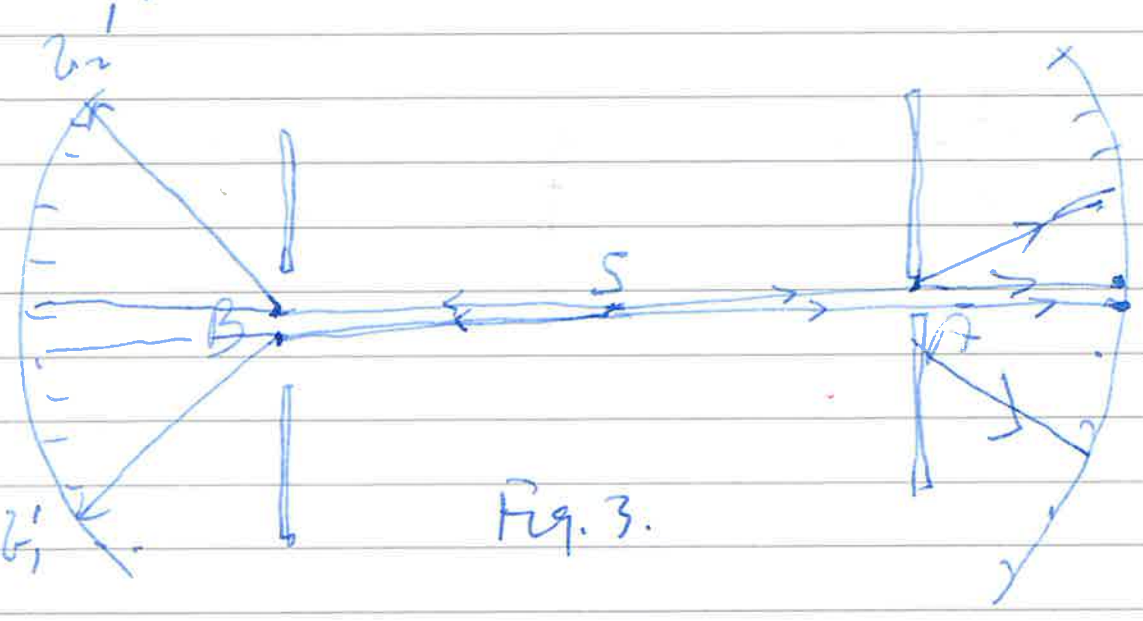


Fig. 3.

But this argument ~~conflates~~ misunderstands the nature of the EPR correlations. They arise from an infinite incoherent line source, so we would always get wide angle scatter, irrespective of the width of B (see Figs 4 & 5)

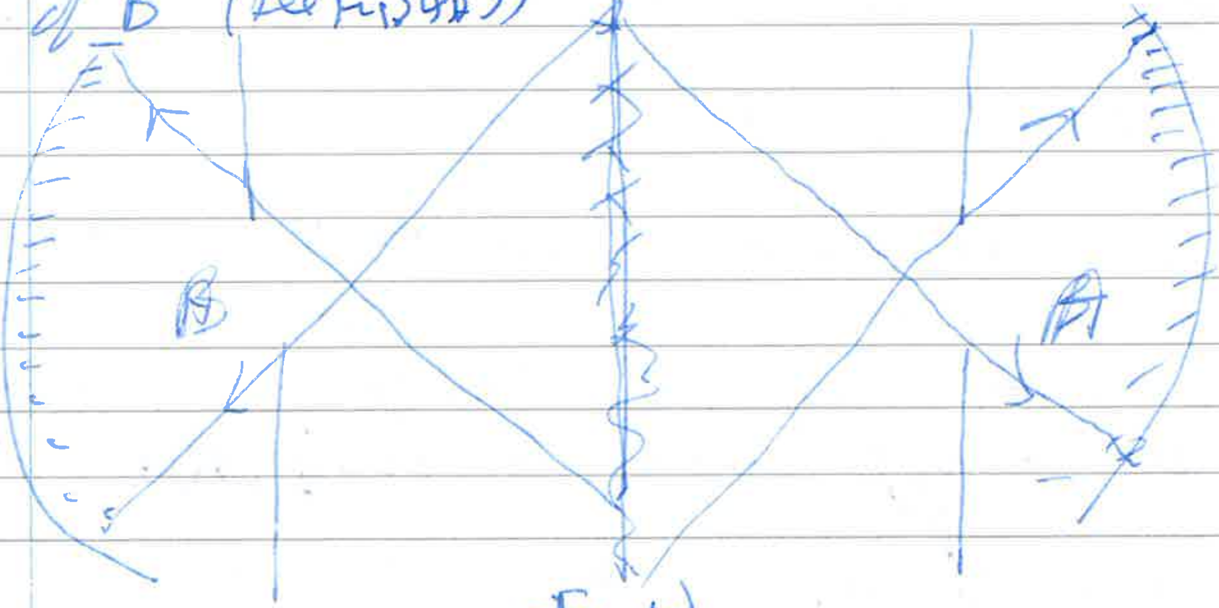


Fig. 4)

A. Sudbury "Popper's Variant of the EPR Experiment does not test the Copenhagen interpretation" Phil. Sci. 52 (1985) 470–476.

H. Krips: "Popper, Propensities, and Quantum Theory", BJPS 35 (1984) 253–292

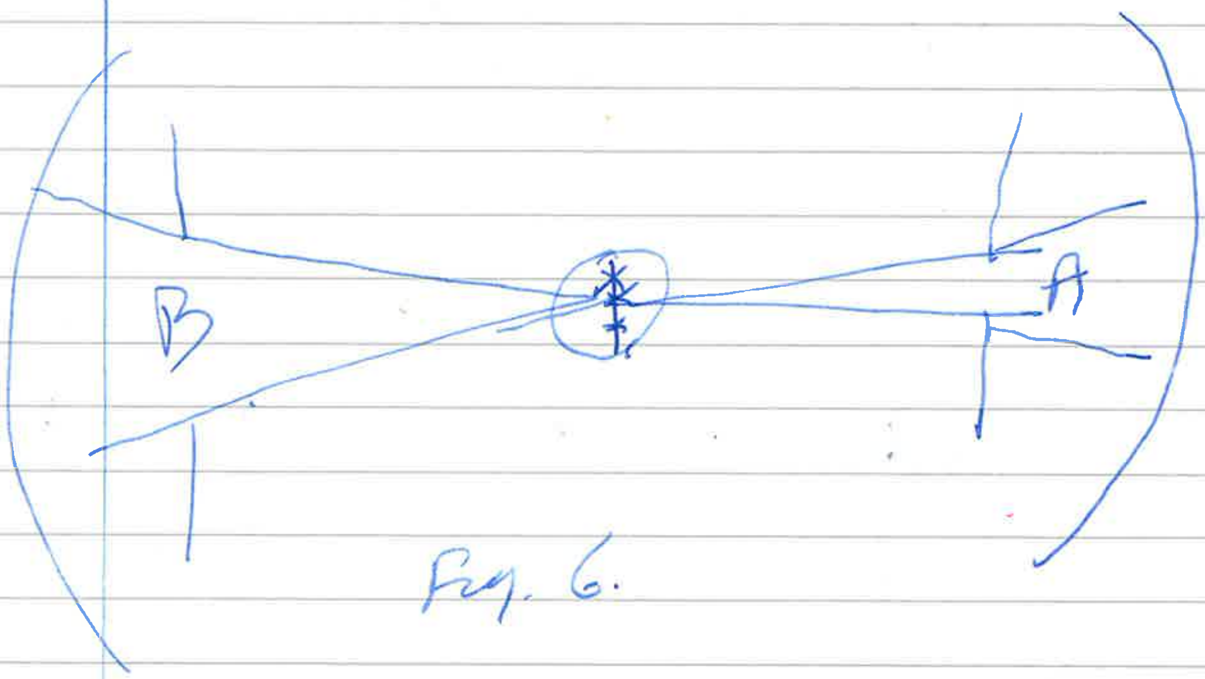


Fig. 6.

* Insertion We indeed can give a general proof that ~~new~~ counters on the left cannot fire by selecting events with a narrower slit on the ~~left~~ right, as follows.

Consider a general 2-particle state that correlates two observables A & B.

$$\Psi = \Sigma\, c_n\, |a_n\rangle\, |b_n\rangle$$

where a_n is an eigenvalue of observable A on the right and b_n – " – — B on the left

Now consider any two observables C on the ~~right~~ left and D on the ~~left~~ right, ~~such that $\mathrm{Prob}^{\Psi}_{D}(d_j) \neq 0$ for every~~

~~element of $\mathrm{Prob}^{\Psi}_{C}(c_i) = 0$, then some~~, then we have

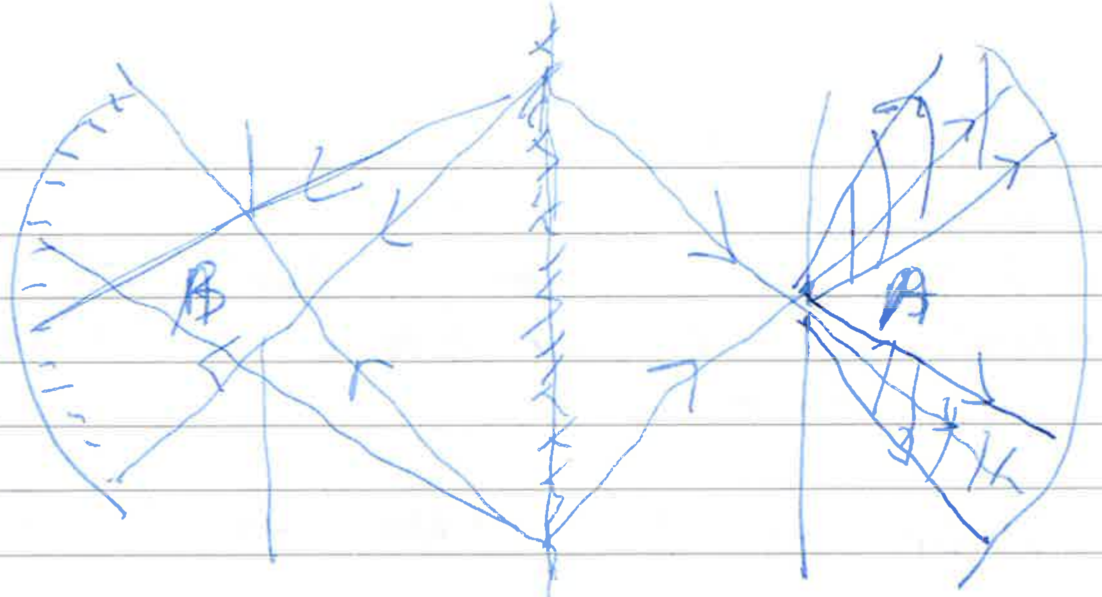


Fig. 5.

Another way to think of this, is that, as we narrow down the source, we lose the momentum correlations.

So a narrow beam on the right, does not correlate with a narrow beam on the left. (see Fig. 6)

So the ~~experiment~~ ~~experiment~~ procedure ~~would also say~~, by narrowing the slit A produces no change in the range of electrons passing behind B. *

Popper's thought experiment was widely criticised (see, e.g. Sudbery (1985) and Krips (1984)), for broadly the reasons I have given.

$$\mathrm{Prob}_C^{\Psi}(c_i) = \sum_j \mathrm{Prob}^{\Psi}(c_i \,\&\, d_j)$$

$$= \sum_j \mathrm{Prob}^{\Psi}(c_i | d_j)\, \mathrm{Prob}^{\Psi}(d_j)$$

It follows that if $\mathrm{Prob}_C^{\Psi}(c_i) = 0$ and $\mathrm{Prob}^{\Psi}(d_j) \neq 0$

then $\mathrm{Prob}^{\Psi}(c_i | d_j) = 0$

i.e. selecting a subensemble by conditionalizing on the right by an event that has non-zero probability of occurring cannot convert a zero probability for c_i into a non-zero probability

Insertion
* He also has a general argument against the possibility of 'internal' prediction or self prediction, because if prediction is known before t', this knowledge will modify the prediction.

II, The Open Universe p. 39 (after Duhem Aim & Structure)

note on Landé's blade Infinite regress of probabilities over initial conditions to explain stable frequencies

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cont. from previous insertion.

In order to apply this to Popper's experiment, just take D = measure position of the right particle and C measure momentum of the left particle

2. Indeterminism and Probabilities

Popper's approach to the quantum theory is based on two main ideas.

1) The prevalence of indeterminism in physics

Instead of the slogan "All clouds are clocks", Popper prefers "All clocks are clouds" (See Of Clouds and Clocks, Objective Knowledge, p. 215)

His arguments for indeterminism are based partly on instabilities that arise even in classical mechanics. For example, he quotes the well-known Hadamard #1 example of motion on a bull's head. [illegible] Or again the example of Landé's blade. ✱

But he also attacks metaphysical determinism on the ~~following~~ grounds

(a) If the future is 'coiled up' in the present, this denies the reality of time as initiating real novelty in the universe.

In his 1950 conversation with Einstein, who defended determinism (God does not play dice...) Popper referred to Einstein as Parmenides, the denier of genuine change. Popper's real motivation however is his belief in human freedom, the unpredictability of a Mozart symphony or a Beethoven Sonata, the development of arguments and theories, the denizens of his World 3 that cultural evolution is outside the purview of World 1 alone and that World 1 is affected by World 3 via World 2, and so on.

2) For these reasons Popper thinks that probabilities in physics cannot, in general, be epistemic. How could human ignorance produce genuine physical effects?

✕ cp also Sixth Thesis, Postscript III, p 54-55.

NB The Great Quantum Muddle is the view that Heisenberg relations are statements about the impossibility of certain measurements due to the non-existence of the entities measured (Postscript III p. 5), instead of scatter relations limiting state preparation

cp p. 52 where the G.Q.M. is attributing distributions as properties of the particle rather than a population of particles'

cp also p. 211 A theory in most cases depends on its capacity to provoke rational criticism, and to inspire attempts to supersede it by something better.

Popper originally held a frequency view of probability, but the production of stable limiting frequencies (i.e. of random sequences) was for Popper a physical fact that needed explaining in an objective notion of tendency, and this led him in the 1950s to his the propensity interpretation. This he regarded as particularly well suited to explicating the scatter relations which he used for interpreting the uncertainty relations in quantum theory.

3. State Preparation and Measurement

Popper regarded the Heisenberg relations as a limitation on our ability to produce homogeneous ensembles with precise values of x and p for example.
In his notorious 1934 thought experiment he believed he could achieve such an ensemble, but when he realized that fixing p disturbed x just as much as fixing x disturbed p, then Popper gave up this possibility.
So Heisenberg had discussed a limitation on state preparation.
But when we measure x or p this is a backward looking exercise as contrasted with the forward-looking exercise of state preparation, and such measurements are necessary to test the scatter relations

3.(~~Popper says he has no prior commitment to sharp values of p & q in all states, ( ) but sees no argument against that view.~~ * }

* See Postscript III p189-190

cf Popper's example of the soldiers equipped
a pocket roulette wheel etc
Postscript III p. 190.

II Feyerabend (1968) fn

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① footnote Regarding the propensity as a property of ~~the~~ Calls is, for Popper, like treating the average height of the people in the room as a property of each particular person in the room. He sometimes referred to this as the Great Quantum Muddle.

But on my view B approach it does seem perfectly legitimate to regard ontological propensities as properties of the reality rather than the set-up.

Moreover Popper says that he believes that between interactions particles follow Newtonian st.-line trajectories, but when interactions occur they get deflected in an intrinsically stochastic fashion*. This is what produces the quantum mechanical scatter.

As an analogy Popper often refers to the pin-board, in which the balls roll deterministically between impacts with the pins. The statistical distribution is the manifestation of a propensity to produce individual results the general position of the rolling ball on the pin or ~~table~~ board. This propensity is a property of the pins ⊙ pins and balls ~~just as much of the rolling b~~ rather than just of the balls. Changing the pins changes the propensity — they are like a set of stochastic fields of force confronting the ball. Popper sees this as explaining, in a general sort of way, the '2-slit experiment'. The closing of a slit is like removing a pin on the pin-board. Even if the ball on a particular occasion never hits the pin, nevertheless the propensity changes. Popper of course stresses (in response to a critique of Feyerabend)# that the pin ~~table~~ board does not exhibit the characteristic interference phenomena of the 2-slit experiment — to explain that is a matter for the physics of propensities. But he also believes in the Landé approach that the effect of the two slits on the beam of electrons is related to the periodicity of the structure to the separation of the slits, which controls the transfer of momentum to the electron as it passes through ~~a single slit~~ one of the slits. If we close a slit we change the sort of physics that the electron is interacting with and hence the character of that interaction.

Because of Bohm's commitment to determinism Popper never liked the Bohm interpretation and the non-local effect of the quantum potential. So how did Popper react to the Bell inequalities and the proofs of nonlocality in quantum mechanics? Popper made here two sorts of comment. Firstly, ~~even~~ if the experiments and their interpretation were taken at face value, then he regarded the Aspect experiment, for example, as a crucial test of the Lorentz versus the Einstein interpretation of the relativity equations. Instantaneous action would call for a privileged reference frame, an aether frame if you like.

But Popper also leaned to the view that the theoretical proofs of the impossibility of local hidden variable theories of experiments such as Aspect's might contain technical flaws. He lent support here to the work of Angelidis who sought to demonstrate local models of these experiments. My last correspondence with Karl was concerned with querying the validity of this work. Karl himself, admitted the whole matter was too technical for him to fully check everything, but urged that

Insertion ⊗ As far as I know Popper never commented on Fine's discussion of the problematics of joint distributions for incompatible observables (see Fine ~~BJPS (1973)~~ "~~On the Completeness of QT~~" in ~~(Suppes (ed.) Logic and Probability in QM, Reidel, Dordrecht,~~ 1976, 249-281) and "Logic, Probability, and QT", Phil Sci 35 (1968) 101-111.

II. Postscript III, p.78, n 2 re. D.

Postscript III, p 6 'The strongest reason for my opposition to the Copenhagen interpretation is its claim to finality and completeness'

Postscript III, p. 103 'By understanding I do not mean ... the building of models in terms of a superseded theory — but [illegible] [illegible] to be criticised in rational terms

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Insertion ⊙ At first sight it might appear that with Popper's emphasis on indeterminism, he would favour the stochastic 'hidden variable' approach. But in fact his commitment to deterministic behaviour between interactions coupled with his doctrine of faithful measurement means that the measurement outcomes are deterministically related to the state of the particles after they have left the source. Hence the deterministic proofs of the Bell inequality are the ones that need to be examined, consistently with Popper's views as he has expressed them in other contexts.

Dingledine's work should be referred to in the literature. This is something I ~~hope~~ propose to do on another occasion. ⊙ Greenbaum

4 P~~opper on~~ The Collapse of the wave function:

This Popper regarded as a quite unproblematic consequence of conditionalizing a probability distribution on the outcome of an experiment #. When the coin lands heads, the probability of heads jumps from ½ to 1, and the collapse of the wave function is just an instance of this.

Let us look at this from the point of view of joint distributions

Footnote [In standard probability theory → $P(A/B) = P(A \& B)/P(B)$, provided $P(B) \neq 0$. {Popper's own approach to probability theory starts with conditional probabilities and then proceeds to joint probabilities, essentially defining $P(A \& B) = P(A/B) \cdot P(B)$.}]

But either way seems committed to joint distributions such as $P(x, p)$ [for ~~[illegible]~~ incompatible observables such as x, p.]

By EPR argument Popper thinks that x and p must exist, ~~so~~ and ~~possibly~~ seems he believes that $P(x, p)$ exists, although as Arthur Fine has stressed, this only follows if x and p are regarded as random variables on a common underlying probability space. Question: So what is the status of joint distributions and simultaneous measurability in quantum mechanics?

Suppose we measure an observable Q and find the value q so that the new state (according to the projection postulate) is $|q\rangle$. If now we measure an incompatible observable Q' and find the value q', then it seems reasonable to claim that in the state $|q\rangle$, Q has the value q and Q' the value q'. Of course we cannot use this knowledge to predict the value of Q after we measured Q'. This might well differ from q, due to the disturbing effect of the measurement of Q'.

But can we measure Q and Q' when the state ψ is not an eigenstate of Q (or Q')?

A typical proposal here is to measure not an observable, call it V which is compatible with Q and has the same numerical eigenvalues as Q' and in the state ψ, has the same probability distribution as Q'. So Q' and V are matched probabilistically, but it does not follow that on a particular occasion the result for V is the same as the result we would have got if we had measured Q'.

The classic example of this is the time-of-flight measurement of momentum, i.e. using $V = \frac{m(x_2 - x_1)}{t_2 - t_1}$ and then measuring x_2 and x_1 ~~(t_2 sufficiently large)~~. The x_2 measurement allows us to infer the value of V, which is distributed probabilistically ~~in accordance with~~ the same way as the momentum scatter generated by the initial measurement of x_1. But does the V measurement give the same result, on a particular occasion, as a 'direct' measurement of momentum e.g. by sending in a magnetic field, & using the

* but this is something that cannot
be checked (tested?)

Doppler shift approach to estimate the velocity. Note that for all these direct measurements, (assuming they are of the so-called first kind) the results of one procedure can be checked by applying the other procedure, since they are all compatible procedures. But in the case of the time-of-flight approach, after the x_2 measurement, the momentum is disturbed, so the value before the x_2 measurement cannot be checked by a subsequent direct measurement.

Nevertheless, if we assume uniform rectilinear trajectories for the particle after the X_1 measurement, as Popper does, then V must be measuring the momentum.*

What about joint distributions? The joint distribution for the results x and p of measuring X and V are of the form $\text{Prob}(x, p) = \delta(\frac{mx}{t} - p)\,\text{Prob}(x)$, which certainly returns the right marginals for x and p. But this is only for a particular state. ~~Exact~~ Joint distributions can always be defined for particular states, e.g. take $\text{Prob}(x \text{ and } p) = \text{Prob}(x) \times \text{Prob}(p)$. This certainly returns the right marginals.

But if we only ~~the~~ ask the question, is there a QM observable that measures x and p and returns the right marginals in all states, the answer is NO (see Fine (~~197~~ 1973 b) or Fine (1982)). Constructions in the literature (e.g. Wigner (1932)) ~~so~~ that do give the right marginals in all states, do not give positive state-independent values for the joint distribution so do not qualify as bona fide probabilities.

* Note generally conditional probabilities in QM are best thought of as conditionals with probabilistic consequents

Prob (A/B) = p means B □→ (Prob(A) = p)

not as always have joint distributions on a phase-space

Popper on Q. Logic

cf. "Birkhoff and Von Neumann's Interpretation of Quantum Mechanics"

Nature 219 (1968) 682-5.

Re Popper: Criticizes the B-Von. 1936 QL paper on the grounds that Popper claims he can prove the lattice is forced to be distributive.
Reply to Popper by Ramsay and Pool, admitting some ambiguities in the B & vN paper, but accuses Popper of misinterpretation of what their intentions were

Let us turn finally to the stochastic effects of interaction on Popper's account. ~~Suppose two particles are moving with correlated attributes towards two measuring devices, e.g. 2-spins in the Bohm version of EPR using the singlet spin state of two particles. If the interactions with the~~

So it is difficult to fit joint distributions into the formalism of quantum mechanics, and Fine has argued that we should reject them. Again it would have been interesting to know Popper's reactions to these moves.*

Conclusion: Popper's stance (Postscript III p 6)

'The strongest reason for my opposition to the Copenhagen interpretation is its claim to finality and completeness'.

I entirely agree that we should not ~~dogmatically prevent certain questions being formulated and answered in a theoretical framework since this contravenes the critical approach to knowledge~~ ~~notably~~ rule out criticism by fiat. Popper has also done a great service to the philosophy of QM by emphasizing the distinction between measurement and state preparation and spear-heading the resistance to the dogmatic tranquillizing philosophy of the Copenhagenists. Because some detailed arguments are flawed, this does not mean that his overall influence has not been abundantly significant.